Joint formation in ultrasonic welding compared with fretting phenomena for aluminium

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Joints between aluminium sheets have been formed using two different processes. The first process is ultrasonic welding using a vibration frequency of 20 kHz. The second process is fretting where two sheets are clamped together and an oscillatory relative movement of small amplitude is applied to them. The frequency is 30 Hz and the amplitude is 5 μm. After a certain number of vibrations a strong joint is formed between the sheets. The following parameters were chosen to be equal for both processes: the amplitude of the relative movement in the contact plane, the contact pressure and the number of vibration cycles. The joints obtained from both processes were examined using tensile shear tests, scanning electron microscopy and metallographic sectioning. We conclude that both types of joints are very similar and consequently formed by the same mechanism. It follows that joint formation in ultrasonic welding and in fretting of aluminium must be ascribed to plastic deformation of an interfacial layer. (In our case about 30 μm thick). Diffusion and recrystallization do not play an important role.

Introduction

As to the joint formation in ultrasonic metal welding no generally accepted theory exists. A number of possible basic mechanisms, which are mentioned in the literature, are reviewed in the next Section.

Fretting occurs between contacting metal surfaces which undergo small oscillatory relative displacements. The first stage of fretting i.e., the formation of junctions (microwelds) seems to be analogous to ultrasonic metal welding. The main difference is the lower vibration frequency of the fretting process, which is roughly x1000 lower than the frequency of the ultrasonic welding process.

To verify this analogy we made ultrasonic welds in aluminium and compared them with aluminium joints obtained by fretting. The parameters (pressure in the contact plane, relative vibration amplitude in the contact plane and number of vibration cycles) were chosen to be almost equal in both the ultrasonic welding and fretting experiments. The aim of the comparison was to investigate the mechanism of joint formation in ultrasonic welding of aluminium.

For the study of joint formation the fretting process has several advantages:

a) Because of the low frequency the process can be followed cycle after cycle. The growth of the joint can be studied easily this way.

b) During fretting no gross temperature rise occurs, so that melting, diffusion and recrystallization cannot play a role.

In our experiments the joints formed during the first stage of the fretting process were not broken because of the relatively low amplitude and the small number of cycles. The word 'fretting' is connected with the formation of wear debris (second stage of fretting). We, however, use 'fretting' in the sense of 'the first stage of fretting using relatively small amplitudes and few cycles'. (This type of joint formation could be called 'subsonic welding'.)

Ultrasonic joining

In ultrasonic metal welding the parts to be welded are clamped between a 'sonotrode' and an anvil (Fig. 1). The 'sonotrode' vibrates parallel to the interface of the two parts and after a certain time a joint is formed.

The frequency of vibration is generally between 15 and 100 kHz. The vibration amplitude of the 'sonotrode' can range up to 30 μm. The bonding time depends upon material properties and lies between 0.1 s. and 1 s. The clamping force is so chosen that the pressure in the interface is about 0.3 times the tensile strength of the material.

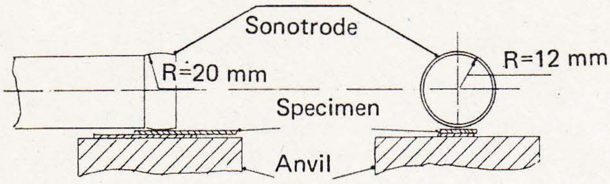


Fig.1 A possible arrangement for ultrasonic welding of sheets.

In order to join metals, clean surfaces must be brought together within a distance comparable to the interatomic distance. Interatomic attraction then causes bonding. Such close contact can be obtained in the following ways:

1) Melting of an interfacial layer
2) Plastic deformation of the contacting surfaces
3) Recrystallization of the contacting surfaces.

O[illegible]er effects such as diffusion and mechanical interlocking ar[illegible] also considered as phenomena causing joint formation:

Melting

With regard to interfacial melting, only a limited number of observations suggest that melting occurs. In the majority of cases however there is strong evidence of the absence of melting.

Ainbinder and Tikhomirova [1] observed globular oxide inclusions in copper after a weld time of 2 s. They concluded that local melting took place. Frisch *et al* [2] reported material being squeezed out of the interface during welding of stainless steel in vacuum (time ~1 s.) A highly plastic state of the material is assigned as an explanation.

Weare, Antonovich and Monroe [3] suggested melting but did not observe any evidence.

No sign of melting was observed by many others [4 to 11]. This is consistent with temperature measurements in the ultrasonic bond zone which fall below the lowest melting point of the bond materials (see Table 1).

Plastic deformation

In regions where the surfaces are in contact lateral vibrations bring about shear forces in the interface during ultrasonic bonding. Plastic deformation is observed which causes removal and/or dispersion of surface films (e.g., oxide layer, adsorbed gases, lubricant films) [3, 5,15 to 18]. By the same action clean surfaces are brought close together and metallic adhesion can occur [3,4,8,9,12,13,19,20].

Recrystallization

The shape of a surface changes during recrystallization. Hence crystallites can grow one against the other to form atomic contact between two surfaces [21]. Recrystallization is reported by Okada *et al* [14] in ultrasonic joints of Cu, Zn and Al, Ainbinder *et al* [1] in Cu and Jones *et al* [4]

Table 1

Maximum temperatures observed during ultrasonic bonding of different materials

Author and year			Bonded material	Melting point of lowest melting material T_m in ^{0}C.	Maximum observed temperature in ^{0}C.
[illegible]ndin	12	1960	Chromel-Alumel	1400	370
"	13	1961	Fe-constantan	1300	600-850
Weare	3	1960	Monel-Cu	1080	230
Jones	4	1961	T3 alclad Aluminum	660	470
			CP-copper (to itself)	1080	300
			Fe (to itself)	1450	660
Ainbinder	1	1963	Al (to itself)	660	630
Okada	14	1963	Al (to itself)	660	500
Daniels	8	1965	Various materials		40% of T_m
Ginzburg	15	1967	M3 copper	1080	730
		–	Cu-Al	660	250
Hazlett	9	1970	Fe-constantan	1300	260
			Cu-constantan	1080	260
Joshi	16	1971	Au (to itself)	1080	
			Au-Al	660	80
			Au-Cu	1080	

in 2014-T6 aluminium and nickel. The last authors state that the role of recrystallization is by no means established.

From X-ray diffraction patterns of the welded zone Heymann and Pusch [19] could not detect any recrystallization. The temperature reached during welding does not necessarily exceed the recrystallization temperature (see Table 1). Further, the bonding time is, in most cases, short compared with the time required for recrystallization, which of course depends strongly upon the temperature. (In the case of the aluminium used in our experiments 30 min storage at 540°C did not cause any recrystallization). We may conclude that the influence of recrystallization, if any, on joint formation is not understood.

Diffusion

It is evident that intimate metallic contact must occur before diffusion can take place. Hence in ultrasonic welding diffusion must be considered as a phenomenon coming about after bonding i.e., bringing surfaces into close contact.

Evidence for bulk diffusion in a Cu-Al joint is given by several authors [15,17,22]

Okada *et al* [14] observed diffusion by means of an X-ray microprobe in a Cu-Ti joint (10 μm diffusion depth into Cu and 40 μm into Ti).

Ginzburg *et al* [15] remark that it is impossible to account for the observed diffusion phenomena by the measured temperatures. They suggest that diffusion is stimulated by plastic deformation. Kulemin and Mitskevich [23] investigated the enhancement of diffusion under the influence of ultrasound. The diffusion constant could be increased by a factor 7. The times, however, are very long (1-3 hours) compared with ultrasonic welding times. As yet, therefore, no conclusions concerning diffusion in ultrasonic welding may be drawn from this work.

No detectable diffusion is reported by Daniels [8] in a Cu-Ni joint and Joshi [16] in a Cu-Au joint; both using microprobe analysis.

Hazlett and Ambekar [9] observed Cu-constantan joints with the scanning electron microscope. From micrographs a faint evidence of grain-boundary diffusion could be concluded. However they did not observe such a phenomenon in a Fe-constantan joint.

Mechanical interlocking

A phenomenon which can also play a role in the ultrasonic joining of metals is mechanical mixing and interlocking. This phenomenon is observed with scanning electron microscopy by Hazlett [9] and Joshi [16]. It points to plastic deformation without appreciable metallic adhesion.

Fretting

When metal surfaces are in contact and undergo minute oscillatory relative displacements fretting can occur. The vibration frequency can go up to about 100 Hz and amplitudes up to several hundreds of microns. Fretting is a complex of adhesion, wear phenomena and chemical reactions [24]. Thomlinson [25, 26] was the first to discuss this phenomenon and called it "fretting corrosion". Later, the term fretting was generally used.

A review concerning the phenomenology and the mechanism of fretting is given by Hurricks [27]. A very brief outline of the generally adopted theory follows here:

In the first stage, oxide layers and lubrication films are disrupted by the oscillatory relative movements of the contacting asperities. By plastic deformation clean metal comes into contact and junctions or microwelds are formed by metallic adhesion [28,29]. In the second stage of the process, these junctions are broken and wear debris is formed. In a reactive atmosphere chemical reactions (usually oxidation) can occur at the interface; reaction products are then formed. A progressive damage of the surfaces is observed.

Apparatus

Ultrasonic equipment

The apparatus for ultrasonic joining was developed in our laboratory and consists of:

a) a piezoelectric transducer [30]

b) a bicylindrical amplitude transformer which is spherically thickened at the end to form the weld tip (Fig. 1).

c) an anvil, which can pneumatically be pressed against the weld tip

d) a generator with timer unit. The generator is automatically tuned at the resonance frequency of the vibrating system. The maximum electrical power is 400 Watt and the nominal frequency is 20 kHz. Voltage and current at the transducer terminals and amplitude at the weld tip can be monitored.

Fretting apparatus

For fretting experiments a simple apparatus was built (Fig. 2). The testpieces are two sheets. Sheet 1 (dimensions 40 x 12 x 2 mm^3, see Fig. 2) is fastened upon an anvil, the other sheet 2 (dimensions 40 x 12 x 1 mm^3) is fixed to a lever, which has the centre of rotation P. The middle of this plate is situated over a rectangular hole in the lever.

On the other end of the lever a vibrator is mounted (not in the fig.). The frequency is 30 Hz. Hence, by vibrating the lever, sheet 2 can make an almost linear movement in the direction AA. The maximum vibration amplitude at A is 40 μm. The middle of the moving testpiece 2 is pressed upon the fixed sheet 1 by means of a spherical pin. The radius of the end of the pin is 6 mm. When the lever vibrates the pin can follow the motion of the upper test-piece. At the end of the vibration period a joint is formed, between the two test-pieces, immediately below the pin. The amplitude of the vibration is measured at A by means of a "Fotonic Sensor" (a non-contact optical apparatus manufactured by Mechanical Technology Inc., Lathem, New York, USA). The sensitivity is 0.2 μm. The shear force in the fretting zone is monitored by means of a strain gauge.

Experimental results

Experiments

Aluminium sheet material was used. (Al $\geqslant$ 98%. Si $\leqslant$ 1%, Fe $\leqslant$ 1%; Vickers hardness 38 VPN; tensile strength 120 N/mm^2.)

The rolled surface did not undergo any treatment except degreasing with acetone. Experimental parameters are given in Table 2.

Tensile shear tests

Tensile shear strength of the ultrasonic welds and the

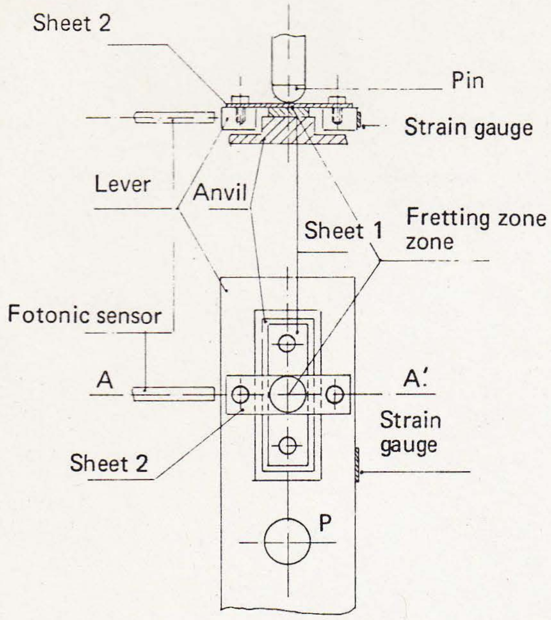


Fig. 2 Top view of the fretting apparatus with a section through AA'.

joints made by fretting was determined (Table 2). The welded area of the joints was estimated by means of a microscope using an ocular with a scale division.

In fretting, when using larger amplitudes and/or a greater number of cycles than in the experiments described in Table 2,the joints are broken during the fretting process.

Initially a fatigue striation pattern is observed at the periphery of the fretting zone in the peeled joint, resulting in a reduction in joint shear strength. An amplitude of 10 μm and 5000 cycles results in an almost completely destroyed joint area (second stage of fretting).

Scanning electron microscopy

Peeled joints were examined with a scanning electron microscope. The micrographs of an ultrasonic weld are shown in Fig. 3. Fig. 4 shows a joint made by fretting.

The dark regions in Figs 3a and 4a are untouched by the processes. Oblong roughened regions, where joining took place, are visible. The longest dimensions of these regions is parallel to the direction of the movement during the processes. These oblong junctions partly overlap or touch.

A characteristic of a rolled surface is the occurrence of "channels and ridges" running parallel to the direction of rolling. In the "channels" no metallic contact takes place and hence we see them as long dark vertical lines on the micrographs (Figs 3a and 4a). These are not observed with specimens which were polished before fretting (Fig. 7).

The broken junctions have the character of ductile broken material. This is shown in Fig. 3b for an ultrasonic weld and in Fig. 4b for a joint obtained by fretting. For these two micrographs the specimens were tilted about 70° to see the relief of the surface.

Metallographic studies

Metallographic sections were made. The samples were vibratory polished and immediately afterwards anodized.

Fig. 5 shows micrographs of ultrasonic joints and Fig. 6 shows sections of joints obtained by fretting. From Figs 5c and 6c we see that the interface has disappeared over large regions. The related Figs 5d and 6d shows that in the whole interface severe plastic deformation has taken place. The long grains of the rolled parent material are fragmented. The thickness of the deformed layer is 15-30 μm, which is confirmed by Figs 5e and 6e.

Especially in the ultrasonic joint, the initiation of cracks can be observed at the periphery of the weld (Fig. 5a). In a joint obtained by fretting this is less clear (Fig. 6a). However, when in fretting an amplitude of 6.5 μm is used cracking is also observed.

Some additional experiments, using polished surfaces, show the growth of the bonds during fretting (Fig. 7). The increasing number of bonds and their increase in length can be seen.

Discussion and conclusions

Analogy between ultrasonic and fretting experiments

Pressure in the contact area and the number of vibration cycles are almost equal for the two processes (see Table 2). The amplitude of the weld tip was 15 μm; the amplitude of the upper plate in the fretting apparatus was 5 μm. In ultrasonic welding slip occurs at three interfaces (a) weld tool - upper joint member; (b) between the joint members; (c) lower joint member - anvil. Also elastic vibrations of the anvil occur.

Thus the amplitude of the relative displacement (= slip) between the two components is smaller than the amplitude at the weld tip. It is also plausible that the slip between the joint members decreases as the joint grows. As to the value of the slip between the specimen little is known. We estimate the value to be between 2 and 8 μm. The reasoning is as follows:

Firstly, in fretting experiments no metallic bonds were found when the amplitude was 2 μm; with an amplitude of 10 μm and 5000 cycles almost all the bonds in the joint were destroyed.

Secondly, a reference [31] (quoted by Dippe [32]) reports a value of 8 μm slip amplitude between the specimen at the beginning of the weld, decreasing to 5μm at the end of the welding period; the tip amplitude is 12 μm. By choosing an amplitude of 5 μm for the fretting experiments we assumed that this would be close to the mean value of the actual slip amplitude in ultrasonic joining.

The formation of joints in fretting

We base the following picture of the fretting process upon the experimental observations. Initially the surfaces make contact at the asperities. The lateral vibration causes normal and shear forces in the contact zone. Thus the surface layer (oxide layer, adsorbed gases, contaminations etc). is locally broken and /or dispersed in the parent material. At those points plastically deformed clean metal comes into contact and the first bonds are formed. The dimensions of these bonds are of the order of 10μm (smallest spots in fig.7a).

These initial bonds grow in the direction of the vibrational movement by repeated plastic deformation. At the growth "fronts" the surface layer is destroyed by deformation. During following cycles new clean material is brought into contact and metallic adhesion occurs. Hence the growth "fronts" of the bonded areas propagate and bonds become

Table 2 Experimental parameters and results

	Ultrasonic welding	Fretting
Thickness upper sheet	1 mm	1 mm
" lower sheet	1 mm	2 mm
Vibration frequency	20 kHz	30 Hz
Amplitude of the weld tip	15-20 μm	
Slip amplitude in the interface*	about 5 μm	5 μm
Number of cycles	6000	5000
Clamping force	900 N	60 N
Welded area	17 ± 3 mm^2	1.3 ± 0.2 mm^2
Pressure in the contact area	53 ± 10 N/mm^2	46 ± 8 N/mm^2
Tensile shear strength of the joints†	55 ± 5 N/mm^2	50 ± 4 N/mm^2

* See opposite † With standard deviation

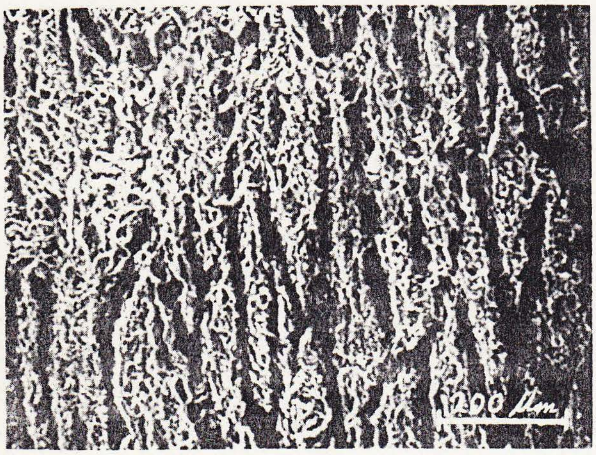


Fig. 3a Scanning electron micrograph of a peeled ultrasonic bond in aluminium. Direction of observation perpendicular to the joint interface.

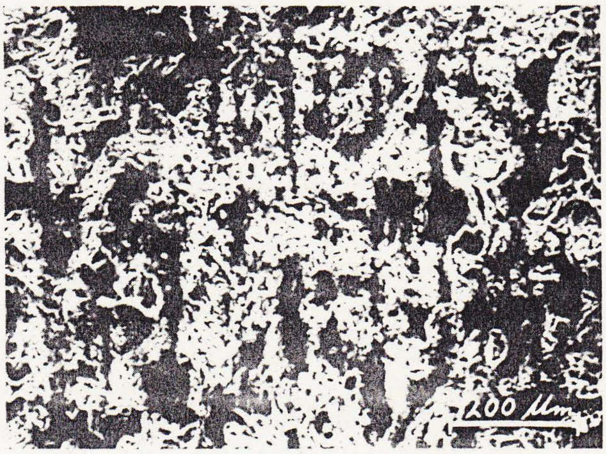


Fig. 4a Scanning electron micrograph of a peeled joint obtained by fretting. Direction of observation perpendicular to the joint interface.

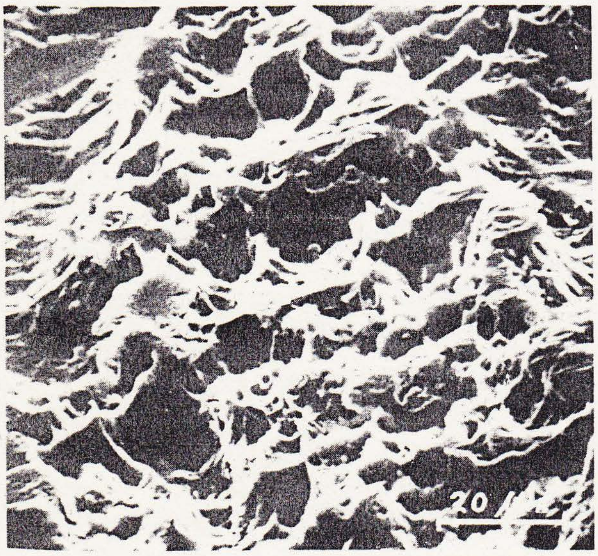


Fig. 3b Scanning electron micrograph of a peeled ultrasonic bond in aluminium.

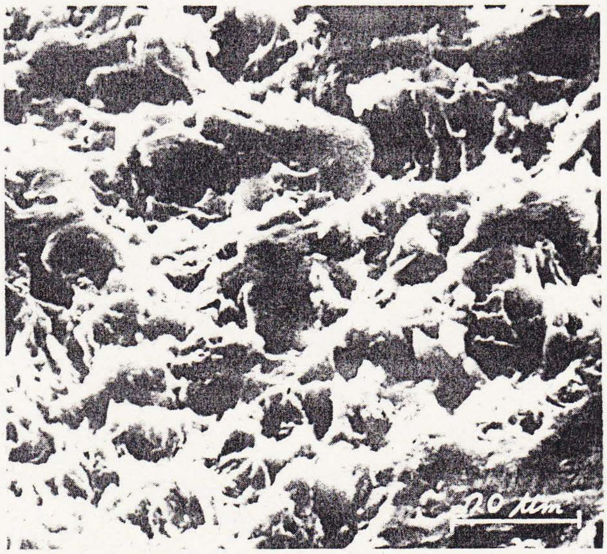


Fig. 4b Scanning electron micrograph of a peeled joint obtained by fretting.

Fig. 5a. Metallographic section of an ultrasonic bond in aluminium.
Direction of sectioning parallel to the vibration direction during joining.
Oberved using unpolarized light.
Region at the periphery of the joint.

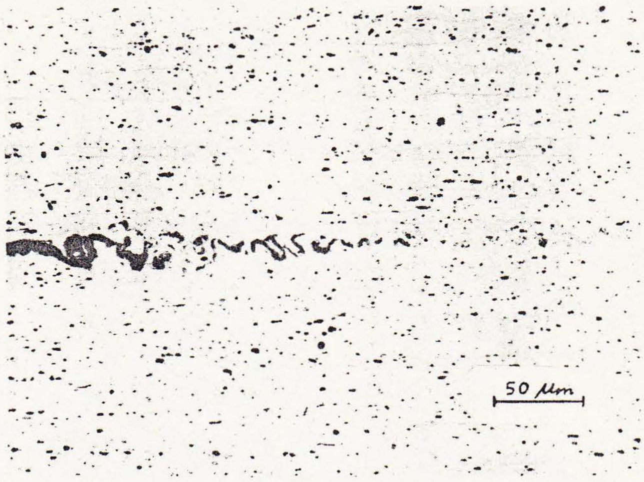


Fig. 6a Section of a joint obtained by fretting. As Fig. 5a.

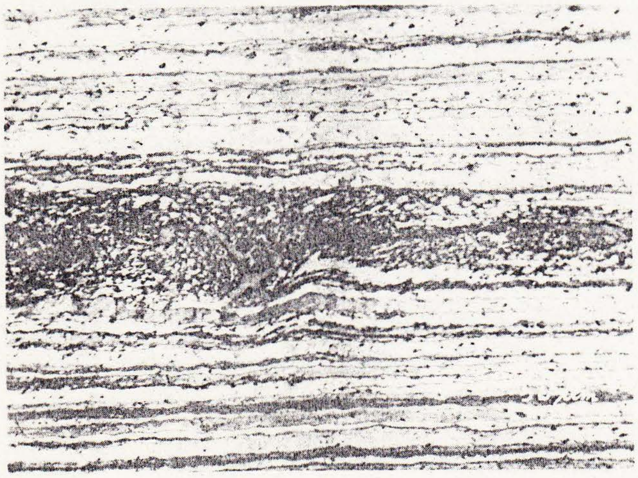


Fig. 5b Section of an ultrasonic bond.
Direction of sectioning as Fig. 5a.
Observed using crossed polarizers.
Same region as in Fig. 5a.

Fig. 6b Section of a joint obtained by fretting. As Fig. 5b.

Fig. 5c Section of an ultrasonic bond.
Direction of sectioning as Fig. 5a.
Observed using unpolarized light.
Region in the central part of the joint.

Fig. 6c Section of a joint obtained by fretting. As Fig. 5c

Fig. 5d Section of an ultrasonic bond. Direction of sectioning as Fig. 5a. Observed using crossed polarizers. Same region as in Fig. 5c.

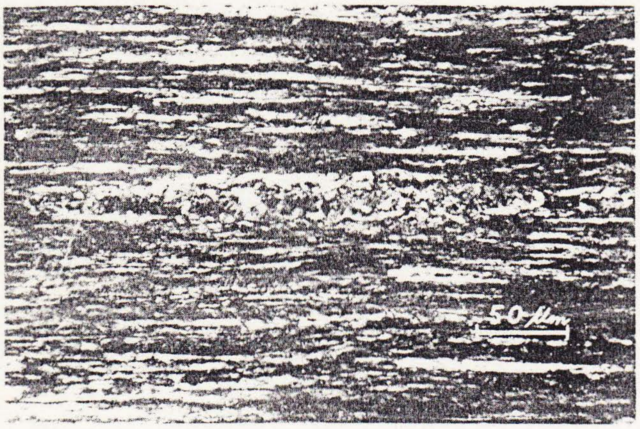


Fig. 5e Section of an ultrasonic bond.
Direction of sectioning perpendicular to the vibration direction during joining.
Observed using crossed polarizers.
Region in the central part of the joint.

oblong in the direction of the movement (Fig. 4a and Fig. 7). Removal of the surface layer occurs simultaneously with the growth of the bonds. As the process continues an increasing number of bonds come into existence. In this manner the plastically deformed interfacial layer is extended and the joint is formed.

The bonded areas grow towards a length of several hundreds of micrometers (Figs 4 and 7) and finally partly overlap. The larger the slip amplitude the faster the growth. Fretting experiments with an amplitude of 20 μm and 200 vibration cycles yield joints with the same strength as the joints mentioned in Table 2 (5000 cycles; 5 μm).

After several thousands of cycles with an amplitude of 5 μm destruction of the weld begins at the periphery (Figs 7c and d). The larger the amplitude the faster the destruction.

Comparison of the results and conclusion

The results of the tensile shear tests examination with the scanning electron microscope and metallographic sectioning show a striking similarity between ultrasonic joints and fretted joints, using almost equal parameters in both processes. It is concluded from the equality of the tensile

Fig. 6d Section of a joint obtained by fretting. As Fig. 5d

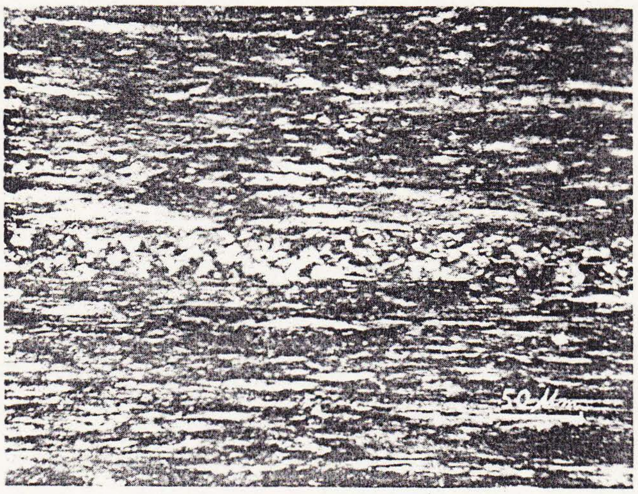


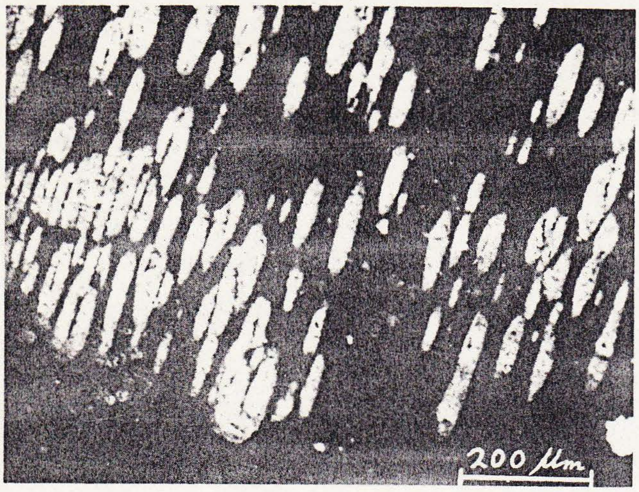
Fig. 6e Section of a joint obtained by fretting. As Fig. 5e.

shear strength, the existence of oblong bonded areas in both types of joints and the observed plastically deformed interfaces in the sections, that the formation of joints in ultrasonic welding and during the first stage of fretting can be ascribed to the same mechanism.

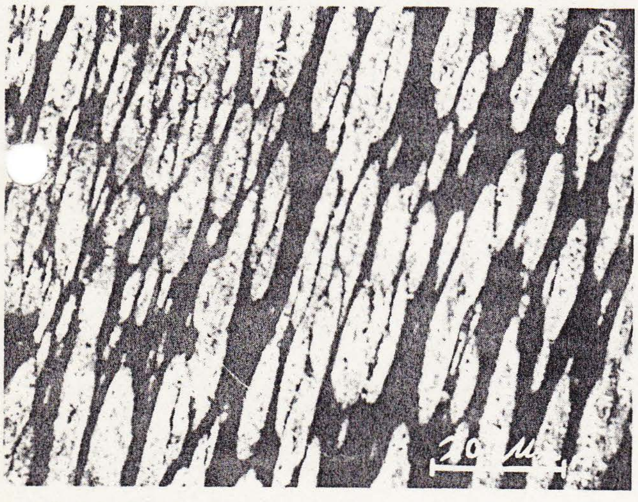
Because of the low power used for the fretting experiment (about 15 mW in the present experiments), gross temperature rise does not occur in fretting. So temperature effects such as diffusion and recrystallization can exert little influence on this process. The only possible mechanism for joint formation under this condition is plastic deformation as already described.

These considerations lead to our final conclusion: Joint formation in ultrasonic welding of aluminium is caused by plastic deformation.

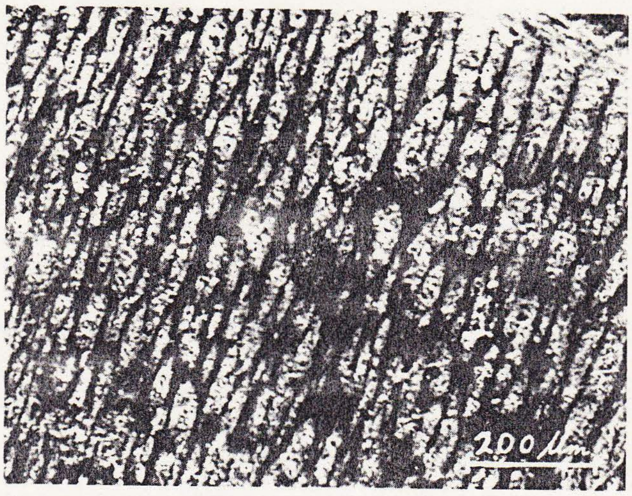
The first bonds occur at the plastically deformed asperities, where surface layers are broken or dispersed and adhesion occurs. These small bonds grow in the direction of the vibratory movement. In this way the whole area is welded after a certain number of vibrations and a plastically deformed interfacial layer, with a thickness of about 30 μm, comes into existence. Temperature effects such as diffusion and recrystallization do not play a role in this process. They can occur during ultrasonic welding but do not primarily cause the formation of the joint.



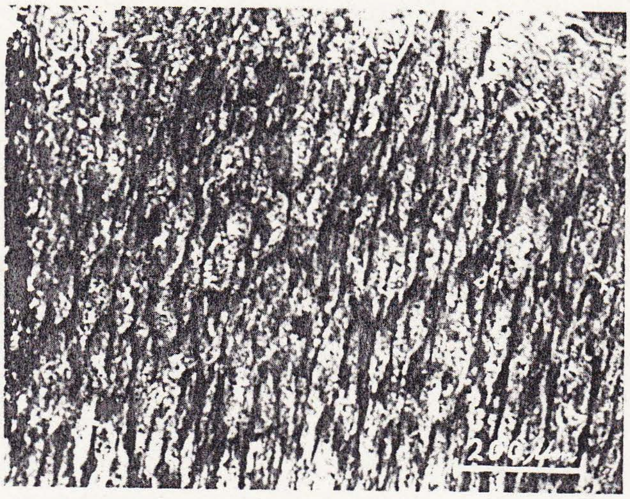
a) after 100 vibration cycles



b) after 300 vibration cycles



c) after 1000 vibration cycles



d) after 5000 vibration cycles

Fig. 7 Scanning electron micrographs of joints obtained by fretting of polished specimens. Vibration amplitude and pressure as in Table 2.

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Discussion

H. FROST (USA) wanted to know whether the plastic deformation in the aluminium sheets occurred by means of actual liquid flow in a very localized region.

J.L. HARTHOORN did not know what the exact mechanism of the plastic deformation was.

B.S. HOCKENHULL (UK) suggested that on aluminium one had a natural oxide film of about 50A° thick. The coherent layer had to be broken down before 'metal to metal' contact was achieved on the bonding surfaces and this required plastic deformation of the substrate.

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